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FEDERAL COMMUNICATIONS COMMISSION
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17 December 1991

Secretary, Federal Communications Commission
1919 M St.
Washington DC 20554

Dear sir:

Enclosed are ten "original" copies of my Comments on the Notice of Proposed Rule Making in MM Docket 87-268. Please provide an individual copy to each Commissioner.

Very truly yours,

William F. Schreiber

William F. Schreiber
Professor of Electrical Engineering, Emeritus

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FEDERAL COMMUNICATIONS COMMISSION
OFFICE OF THE SECRETARY

Before the Federal Communications Commission
Washington DC 20554

In the Matter of
Advanced Television Systems
and Their Impact upon the
Existing Television Broadcast Service

MM Docket No. 87-268
Notice of Proposed Rule Making
November 8, 1991

Comments of

William F. Schreiber
Professor of Electrical Engineering, Emeritus
Research Laboratory of Electronics
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36-545 MIT, Cambridge, Mass. 02139

The opinions expressed herein are those of the author only.

December 17, 1991

Executive Summary

The Commission's decision eventually to terminate NTSC broadcasting in the interest of spectrum efficiency is to be applauded. This makes it even more important to ensure that the selected ATV system will be rapidly accepted by broadcasters, manufacturers, and viewers. Such acceptance obviously depends on the system performance and on the cost of receivers. It also depends on the cost of set-top converters that will enable the very large population of NTSC receivers to be used as long as the public so desires.

Since current picture quality is adequate for a large proportion of programming, particularly in the daytime, consideration might be given to authorizing the transmission of 2 or 3 NTSC-quality programs in each ATV channel during certain hours for the purpose of making more service available to the public and perhaps for providing an additional revenue stream for the broadcasters who furnish free and universal service. The same technology should be used for this service as for the chosen ATV system.

Easy interoperability with other media, with other applications, and with systems of different picture quality is essential in order to realize the potential economic benefits of a shift to ATV. Interoperability is also essential to permit the nondisruptive improvement of the broadcast system over time, a stated goal of the Commission. This issue is particularly important at present because none of the proposed digital systems appears to offer such interoperability.

Finally, the possibility of the use of noncompatible ATV systems in cable and DBS service suggests that the Commission should reexamine its earlier decisions to let these media go their own way.

Introduction

These comments are directed primarily at the technical considerations in ATV as well as the economic and other questions that relate to the willingness of broadcasters, viewers, and manufacturers to accept a new system. They do not deal with the material in sections II, III, IV, and VIII of the Notice.

In general, the actions of the Commission in this matter are to be applauded. Especially laudable are the simulcast decision and the decision to phase out NTSC eventually. These decisions ultimately will lead to a much better system than would have been possible with the receiver-compatible approach. We can now expect more and better service within a smaller overall spectrum allocation. However, there are many substantial technical and nontechnical hurdles to be overcome in reaching this goal. The Commission's reliance solely on market forces to ensure interoperability with other media still presents a significant danger to an orderly transition to a new system, as I pointed out in my comments on the original NOI of 1987 and the further NOI of 1988. We are now witnessing the introduction of a nonstandard digital compression system into DBS service by the National Technological University.[1] Even more important is the Request for Proposals from CableLabs/TCI/Viacom.[2] These schemes have the same goal as HDTV, i.e., sending more information in a given channel. Regardless of their particular merits, it would be in the public interest if they were compatible with the ATV system to be selected by the Commission and used the same technology. At best, the introduction of a number of such mutually incompatible systems, most of which will be made obsolete by the Commission's future actions, will result in wasted investment. At worst, the existence of a large body of equipment of one type may influence the decision of the Commission — a decision that should be based on the public interest only.

Conversion to ATV

It should be recognized at the outset that HDTV has never been attractive to broadcasters, nor is there a grass-roots demand for better picture quality. While technically better pictures and sound are desirable in themselves, the primary reasons for going to a new system are to achieve better spectrum efficiency and for the economic benefits that may accrue to various industries and to American society in general. Broadcasters will spend money on HDTV to protect their market share from competing media, and viewers will buy new sets if they can get more desirable programs or if they have to in order to maintain their current service. A favorable economic effect, on the other hand, depends on having the right transition scenario, on adequate interoperability, and on American manufacturers getting a substantial share of the market for new equipment.

The Commission properly recognizes that service must be provided to current receivers for some time. I now believe that such service must be provided as long as there are any substantial number of these receivers in use for over-the-air reception. Any other policy would prove

[1] Digital Compressed Video Plan, NTU, 700 Centre Ave., Ft. Collins, Colorado 80526, June 1991. The system is already partially operational using equipment from Compression Labs.

[2] RFP for Digital Compression Program Delivery System, 30 August 1991.

politically unacceptable, no matter how far in advance the shut-down decision were announced. The difficulty of turning off NTSC would be greatly eased by the availability of low-cost set-top converters and of inexpensive ATV receivers that provided quality similar to that of NTSC at low prices. This is so important that strong preference should be given to ATV systems that have this capability.[3]

One factor likely to extend the life of NTSC receivers is the very large population of NTSC VCRs. These can be used for many years to play NTSC tapes, of which an enormous number exist. This library of material includes not only commercially made movie tapes but also amateur tapes produced by the rapidly growing number of cameras in the hands of the public. As long as NTSC receivers exist to play these tapes, there will be pressure to continue NTSC broadcasting. To attain the highly desirable goal of getting NTSC off the air, a reasonable alternative such as cheap set-top conversion must be available.

Everyone agrees that the speed of penetration of ATV will be greatly affected by the cost of receivers. In this connection, not enough attention has been directed at the likely cost of receivers for the proposed all-digital systems. A recent article in the NY Times about the successful completion of General Instrument's hardware (a remarkable feat in itself) stated that the receiver requires 10 *billion* operations per second. This is many hundreds of times higher than a high-end personal computer. It is certainly true that the cost of computation is decreasing and its speed is increasing. Yet no one has seriously suggested that such supercomputer power will be available in the near future for, say, $200. Estimates for the time scale likely to be involved in reducing the cost of receiver signal processing to acceptable limits are essential before any decision on standards can be taken.

A possibility that is not mentioned in the Notice is the delivery of two or more separate programs of NTSC quality in a single 6-MHz channel.[4] As current experience shows beyond doubt, today's quality is entirely adequate for a large proportion of programs, including most news programs, soaps, game and talk shows, and sitcoms. Actually, demand for the full quality of HDTV is absent from most daytime programming.

Two interesting possibilities result from this fact. By transmitting at NTSC quality much of the material that does not require full HDTV performance, broadcasters (who provide the free and universal service so cherished by both Washington and viewers) would avoid part of the increased cost of HDTV programming. In addition, they might get an extra revenue stream by renting the newly available spare channels for other than normal broadcasting use. Such dual use, which might be limited to certain hours of the day, ought to make the shift to ATV considerably more attractive to broadcasters.

If these extra channels could be used for such other purposes part of the time, a great deal more

[3]Unfortunately, of all the simulcast systems being tested, this is only true of MUSE, in which this capability was deliberately, and wisely, incorporated from the beginning. The MUSE signal can simply be low-pass filtered to get an alias-free signal with adequate resolution for a low-cost receiver. All the other systems require the signal-processing capabilities of a full-performance receiver to get any picture at all.

[4]As mentioned above, this can readily be done, and should be done, with essentially the same technology that permits sending an HDTV signal in a channel designed for NTSC.

service could be provided without any additional spectrum allocation. In particular, the availability of more channels during the day would greatly expand the possibilities for programming directed at schools and industries. If the Commission feels that this kind of service is in the public interest, then systems that provide this capability ought to be preferred.

Interoperability

Easy interchange of signals with other media, with other applications, and with systems of different picture quality is essential to achieve some of the favorable economic effects of the transition to a new television system. If we use these capabilities as the definition of "interoperability," then the Commission's stated goal of nondisruptive improvement over time can also be attained, along with other desirable features such as scalability and extensibility. Thus interoperability, properly implemented, will not compromise the Commission's goals; it will advance them.[5] The Commission has done an important public service in raising the issue at this time.

The advantages of interoperability are clear. High-resolution imaging is of increasing importance in medicine, multimedia work stations, CAD/CAM/CAE, electronic photography, and many military applications. Important economies of scale will accrue to all these because of the mass-produced components that will appear should broadcast HDTV become successful. Important economies of operation will result from the easy interchangeability of signals among applications. Easy system interchange among systems of different resolution will also permit the desired evolutionary improvement of the broadcast system without making any equipment obsolete.

No one is opposed to interoperability in principle. Everyone would be in favor of it, or at least neutral, if it did not place additional burdens on his own application. This is especially true for broadcasters. The problem, therefore, is to seek technical means to achieve interoperability with negligible additional cost to anyone. I believe this is possible, but only if the problem is properly cast and attacked.

Unfortunately, there is widespread misunderstanding on this matter as a result of the proposals for all-digital terrestrial broadcasting. I do not mean to denigrate any of these systems; much excellent work has gone into them, particularly in the area of source coding. However, *digital broadcasting, by itself, does not automatically facilitate interoperability, nor does the use of analog or hybrid analog-digital signal formats necessarily impede it.* Interoperability can be achieved by using signal representation in frequency space together with the ability to add or delete frequency components easily.[6] These requirements are not met by any of the currently proposed all-digital systems. All four must be completely decoded to baseband before conversion into any other format. There are so many other misconceptions about digital broadcasting that it seems appropriate to attach a detailed discussion in the Appendix to these comments.

[5] The author has held these views since the beginning of the Inquiry. See W.F.Schreiber comments to the 1987 NOI.

[6] See W.F.Schreiber, "A Friendly Family of Transmission Formats," National Assn. of Broadcasters, Las Vegas, May 1989.

Conclusions and Recommendations

\s we rapidly approach the time of decision on HDTV terrestrial broadcasting standards, several issues demand special attention. One is the cost of ATV receivers, which are likely to require immense signal-processing capabilities. Another is the cost of set-top converters to permit NTSC receivers to be used after NTSC broadcasting ends. Finally, interoperability has emerged as an important consideration. Therefore, I believe the following recommendations are in order:

- Require all system proponents to make realistic estimates of the cost of full-quality ATV receivers, NTSC-quality ATV receivers, and set-top converters over a ten-year period following the standards decision. Evaluate these estimates and take them into consideration when the decision is made.

- Require all system proponents to state how their proposed systems can be made interoperable with other media, other applications, and other picture qualities, and how they lend themselves to nondisruptive improvement over time.

- Give consideration to authorizing the transmission of two or three NTSC-quality programs in each ATV channel as occasion demands, using technology compatible with ATV technology.

- Reconsider the Commission's decision to permit arbitrary ATV standards to be used in cable and DBS service, with a view to preserving interoperability.

- Reconsider the Commission's decision not to require any kind of compatibility standards for ATV receivers, with a view to preventing the proliferation of receivers that cannot be used with the forthcoming ATV broadcast standard.

"APPENDIX"

All-Digital HDTV Terrestrial Broadcasting in the US: *Some Problems and Possible Solutions*

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Symposium International — Europe-USA
Paris, 27 May 1991

Abstract

The United States is scheduled to select an HDTV terrestrial broadcasting standard in 1993. The Federal Communications Commission has set up certain requirements, including using a bandwidth of only 6 MHz and having much better interference performance than the current system, NTSC. These requirements mean that the new system will not be compatible with NTSC, so that simulcasting will be required in order to maintain service to existing receivers at least for a number of years. Of the six proposed systems, the four that have a chance of meeting these requirements are remarkably similar. They all use motion-compensated frame-to-frame prediction and application of the two-dimensional discrete cosine transform to the prediction error. Adaptively selected transform coefficients are transmitted digitally, together with decoding information, at a uniform rate of about 20 Megabits/sec to all receivers in the viewing area.

Since receivers in the central city have much higher signal levels than those at the boundary of the service area, the uniform transmission rate wastes large amounts of channel capacity in the central cities where a spectrum shortage is developing due to the rapid growth of mobile services. Alternative transmission methods, both hybrid and all-digital, are available that could raise the spectrum efficiency, thus providing better service to most viewers within a smaller overall spectrum assignment.

In addition to the question of spectrum efficiency, a serious question of reliability is raised by the proposal to use all-digital terrestrial broadcasting at a fairly high transmission rate, especially in view of the lack of experience with such systems, successful or otherwise, anywhere in the world.

The opinions expressed in this paper are those of the author only.

Introduction

The United States is in the process of formulating a standard for terrestrial broadcasting of high-definition television (HDTV). A number of preliminary decisions have already been made by the Federal Communications Commission (FCC), the most important of which, for the purpose of this paper, is that HDTV will be noncompatible with the current system (NTSC) and will occupy a single 6-MHz channel in the normal VHF and UHF bands. The June 1990 proposal of General Instrument Corporation to use digital *transmission* as well as digital *compression* has provoked enormous interest. There are now four rather similar all-digital systems in the competition. Many commentators have assumed that this indicates that the US now leads the world-wide race in HDTV technology, and that the FCC is highly likely to select such a system when it makes its decision in 1993.

The reasons most often given for using digital broadcasting include higher compression ratio, better noise performance, suppression of ghosts and interference, and easier interoperability with nonbroadcasting applications. Sometimes higher transmission efficiency is claimed. All of these reasons appear to be erroneous. What is rarely mentioned as a desideratum is *high spectrum efficiency, i.e., the ability to deliver the maximum number of different programs of a given technical quality to each viewer within a given overall spectrum allocation.* From the regulatory point of view, this must be a primary goal, since there are always more applicants for spectrum than there is spectrum to be assigned.

Systems that deliver the same data rate to all receivers in the viewing area, as do all four of those currently proposed, have high transmission efficiency only in the fringe areas.[1] Failure to utilize the higher capacity available to closer-in receivers necessarily wastes channel capacity in the central cities. This is just where a spectrum shortage is developing due to the rapid growth of mobile systems such as cellular telephone service. This shortage is bound to get worse as more mobile services come to be used. Systems that take advantage of the higher carrier-to-noise ratio (CNR)[2] at closer-in locations can deliver better pictures to most viewers using much less bandwidth. This is not necessarily a question of analog vs. digital, since there are a number of ways to achieve high efficiency in both kinds of systems.

Another result of restricting all viewers to the data rate achievable in the fringe area — hopefully about 20 Mbits/sec — is that very high compression is required, with correspondingly more complex coders and decoders.

An issue that seems neglected in the currently proposed systems is reliability. For all its faults, NTSC delivers some kind of viewable image under atrocious transmission conditions, even with "rabbit-ear" antennas. (The audio quality is nearly always satisfactory in NTSC if the picture is even minimally viewable.) Digital transmission, however, requires some minimum conditions to function at all, and to achieve transmission approximating the theoretical channel capacity requires nearly perfect suppression of ghosts, interference, and frequency distortion. It is instructive to note that there are few, if any, digital terrestrial broadcasting systems in use anywhere in the world for any purpose. The principles have been known for perhaps fifty years, and there are now numerous digital systems in use in wire and cable systems, in satellite broadcasting, and in point-to-point terrestrial communication. One must ask the question as to what has been learned recently to make digital terrestrial broadcasting now seem attractive. In fact, there appears to be little work going on to investigate the problems and to develop solutions.[3]

No doubt, the question of reliability will eventually be answered by field testing. However, American plans are for field testing only the one or two systems that seem best in the laboratory tests. This puts such testing into late 1992, when any serious problem that surfaces will inevitably delay the final decision by the FCC.

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[1] There is no FCC requirement that everyone must receive the same picture quality. All current analog systems have a smooth fall-off in quality with range, because of the inverse-square law.

[2] In this paper, CNR will be used for modulated signals in transmission channels and SNR for demodulated signals.

[3] The Independent Broadcasting Authority in Britain is investigating the feasibility of digital broadcasting in the UHF band. [1] Note that, in Britain, large numbers of low-power transmitters are used as well as a relatively smaller number of high-power transmitters as exclusively used in the US. This greatly reduces the disparity in CNR between near and far receivers. The IRT in Germany is investigating digital audio broadcasting (DAB). [2] A data rate of about 5 Mbits/sec is being tried in a bandwidth of 7 MHz. This is less than one-fourth the rate proposed for digital TV broadcasting in the US.

Possible Alternatives to Terrestrial Broadcasting

There are those who believe that the best path for the US would be to abandon terrestrial broadcasting for television and to reserve the radio spectrum for mobile services exclusively.[4] In their minds, the search for systems that can deliver true HDTV in the admittedly quite narrow over-the-air channel, particularly in spite of severe channel conditions, seems positively quixotic. This is especially the case in view of the possible rewiring of the country with fiber-optic cable direct to every home. Fiber is thought to be able to provide much higher channel capacity with no analog impairments. Other possibilities, all with higher quality and capacity than terrestrial broadcasting, include direct satellite broadcasting (DBS), cable, VCRs, and even large storage systems for "video on demand."

An impediment to any such radical change in the broadcasting infrastructure is that the US is already fully wired. If we were doing this job "from scratch," a strong argument could be made for using fiber in the cities and DBS in the countryside. That is not the case, however. Any change involves abandoning the very large existing investment. There are 1400 television stations in the US; each has a transmitter and antenna; many are owned individually by separate corporations. Virtually none of them wants to abandon this investment in order to make the transition to another transmission modality, particularly one that would be owned by another company that would have to be paid to carry their programs. It is much cheaper to carry broadband signals to the home with the existing system than to build a new one.

Fiber to the home would probably cost $1000-2000 per household, or $100-200 thousand million (US billion) overall. (Some estimates are much higher.) Even today, that is a lot of money. To make such an investment profitable, subscribers would have to spend much more on communications services than they now do. There is little evidence that they are willing to do so. Until such evidence is developed, there will be little incentive for any group to make the required investment.

In addition to cost, I believe that objections would be raised to giving any entity a monopoly on communications to the home. There is still a great deal of concern in Congress about potential abuses of monopoly power, a burning issue within the memory of many.

Satellite broadcasting is much less revolutionary than fiber to the home. There is a chance that some DBS systems will come into operation, but not with the objective of major replacement of other broadcasting modalities. Even for a much less ambitious undertaking, starting a DBS service in a serious way probably involves risking between $.5 and $1 thousand million dollars. To be successful, a DBS system must take many subscribers away from cable, and there is no assurance that this can be done without an extraordinary investment in programming.

A final obstacle to an entirely new broadcasting system is that the FCC appears committed to maintaining the economic viability of the existing networks along with large numbers of affiliated and independent TV stations. It is this infrastructure that provides the free and universal television service that is so treasured in Washington. Even though some 65% of television households are now on cable, most of what is watched comes from the networks and other over-the-air broadcasters. Thus, even cable viewers are

[4]One such service might be a universal personal communication system in which everyone would receive a permanent telephone number at birth. h a system would permit contacting anyone (with his permission, no doubt) anywhere and anytime.

heavily dependent on terrestrial broadcasters for the programming that fills their evenings.

In view of all this, the FCC has stated its intention of setting standards for over-the-air HDTV transmission only. It will rely on market forces to ensure that other media adopt suitably related standards. This leaves the system designer with no choice but to tackle the technically most difficult task, which is that of finding out how to deliver vastly improved picture quality within the existing channels and spectrum allocation and with receivers and other equipment of a cost and quality so that both viewers and broadcasters will be induced to make the required investment.

Regulatory Issues

The FCC is required by the Communications Act to regulate in the public interest. One its most important functions is to allocate spectrum for various purposes and then to assign frequencies to particular licensees, who pay nothing for the privilege of using the airwaves. It carries out this function directly in the public view, using carefully prescribed procedures to ensure that all sides are heard. In allocations and assignment, it must take into account the needs of all claimants. There is a great deal of potential public and private benefit attached to spectrum usage. There are many different wealth-producing uses for spectrum. Therefore, at least for frequency bands for which technology is available, there is almost always more demand than supply.

This situation makes spectrum efficiency a main concern. If technology exists that enables a service to be provided in less bandwidth, the FCC is obliged at least to consider it carefully. It is not out of the question for those who are denied licenses to demand that the FCC make room for them by utilizing the most spectrum-efficient technology available. This may well be the case in HDTV. TV is the most voracious consumer of spectrum, and the US has allocated more spectrum for this purpose than most other countries. It was the fear of broadcasters that the FCC was about to take back allocated but unused UHF channels (that might be needed for HDTV) for mobile radio uses that stimulated the current Inquiry.

The concern of the FCC with spectrum efficiency surely lay behind its preliminary decisions of March 1990. [3] Augmentation systems, in which NTSC is delivered in one channel and enhancement information in a second channel, were ruled out specifically on this basis. The HDTV signal is to be independent of (and therefore incompatible with) NTSC and is to use only one 6-MHz channel. For at least an interim period, all programs broadcast in HDTV must also be broadcast in NTSC in existing channels. All current licensees who so desire will be assigned a second channel for HDTV. Since, in may localities, only taboo channels[5] are available, this means that the HDTV signal must have much less mutual interference with NTSC than two NTSC signals have at present. In effect, it requires that HDTV transmitter power must be much less than now used by NTSC.

Although the FCC has made no ruling about the eventual fate of NTSC or whether the simulcasting requirement will be maintained permanently, it is highly likely that, if HDTV is a success, NTSC will eventually be phased out. If not, we would have a situation in which much better pictures were being transmitted in low power in some channels, while much poorer pictures were being transmitted at high

[5]A taboo channel is one that is allocated but cannot be used in a certain locality, primarily on account of interference. In some localities, low-ower TV stations have been authorized to use these channels. Such service will be terminated if the taboo channels are used for HDTV.

power in the other channels. Such a spectacle is untenable when there are additional claimants for spectrum. The decision to take NTSC off the air at some time in the future would be greatly eased with the availability of low-cost set-top converters, and with the feasibility of building low-cost receivers (with lower performance) for the HDTV signal. This being the case, it would seem important to design these capabilities into the HDTV system from the beginning.[6]

Spectrum Efficiency

Figure 1 shows a generalized image processing system. The channel capacity required for transmission of images of a certain perceived quality depends on the efficiency of both the source and channel coders. The former minimizes the amount of data required to represent the image, and the latter minimizes the power and bandwidth needed to transmit this data to the home through whatever medium is provided.

What we usually think of as "data compression" is a function of the source coder. However, both are involved in "spectrum efficiency," as defined previously. For example, the very poor interference performance of NTSC has the result that, of the 68 channels allocated for television (and that cannot be used for anything else), only about 10 to 20 are usable in any one locality. A hypothetical system that allowed all channels to be used would permit either the allocation of only 20/68 times the overall spectrum for equivalent service, or the use of 68/20 times the bandwidth for each channel, with much better picture quality.

Successful transmission of HDTV in the terrestrial broadcasting channel requires both high compression and high transmission efficiency. The higher the one, the lower the performance that can be tolerated in the other. Conversely, the poorer the one, the higher the performance that is required in the other. The current system proponents have all come to the conclusion that about 20 Mbits/sec can be transmitted; to achieve full HDTV quality with only 20 Mbits/sec requires a very high degree of compression. Whether this degree of compression is feasible with the full range of image types normally used in television, and with the quality that will eventually become available from improved cameras, remains to be seen. Whether economical receivers are possible with such complex systems must be proven. Finally, whether even 20 Mbits/sec can be transmitted with adequate reliability also must be demonstrated.

Beyond this is the question of delivering the same data rate to all viewers, regardless of CNR. The Shannon channel capacity, in equivalent bits per second, is proportional to the CNR, in dB, times the bandwidth, in Hz. [4] Due to the inverse-square law, it thus varies greatly between close-in and far-out receivers, an effect much too large to be countered with antennas. In analog systems, such as NTSC, the increased channel capacity at close-in locations manifests itself as improved SNR in the received images. The gradual decrease of quality with CNR provides a soft threshold that is characteristic of all systems that utilize the channel efficiently. Of course, when the CNR rises above 50 dB or so, the visible improvement ceases, and some spectrum wastage occurs.

Because of the relative strength of the vision and sound carriers in NTSC, as well as the use of high-index

[6] One way to get a particular NTSC station off the air, if it is owned by a licensee who is switching to HDTV, is to distribute set-top converters free to all viewers in the service area. For a cellular-telephone operator who wants the channel, this might be a reasonable investment, depending on the cost of the converter.

FM, good-quality audio is provided even when the picture is extremely noisy. Because viewers are much ›ss bothered by visual than aural noise, the noise-limited coverage of NTSC transmissions is very large, and there is no sharp threshold as would be found in digital systems.[7]

There is no FCC requirement that image quality be equal at all locations; indeed, it is far from equal today. The effect of providing the same image quality to the close-in locations as is found in the fringe areas is that much more bandwidth is required for a given overall quality of service. Depending on the distribution of population in a particular metropolitan area, it may well be found that most viewers have a potential channel capacity more than twice that found at the fringe. In this case, a system — digital, hybrid, or analog — that effectively utilized the channel capacity throughout the service area could provide as good pictures to most of the audience using only half the bandwidth of a system that provided the same service to everyone. From the standpoint of the regulator or the mobile-service operator, the more efficient system is certainly more desirable.

Analog Channel Impairments

Figure 2 shows a complete television system. It is evident that the TV image follows a number of complicated paths from the scene before the cameras to the image in the living room. Each segment of the path has different channel capacity and physical characteristics. For maximum efficiency, therefore, the signal format must be adapted to the path segment. Of all these, the most difficult is the terrestrial transmission link. It is plagued by ghosts, noise, interference, and frequency distortion. It is these channel impairments, and not bandwidth or resolution, that effectively limit picture quality in the home. In audience tests conducted by MIT's Advanced Television Research Program, the perceived difference between studio- and home-quality NTSC was much larger than that between NTSC and the Japanese 1125-line system, both of studio quality. [5] We are so used to these effects that an example is hardly needed, but one is shown in Figure 3. Obviously, if there were some way to eliminate these impairments, picture quality would rise a great deal. Unfortunately, this is not very easy, which is why alternative means of getting pictures to the home have been advanced, as discussed previously. However, due to the convenience and low cost of over-the-air transmission, it is worth seeing whether these problems can be eliminated.

Although digital transmission is often advanced as a means of eliminating these degradations (after all, we don't see ghosts in digital pictures), in reality, the degradations must first be eliminated before it is possible to transmit digitally at anywhere close to the theoretical rate.

Noise and interference rejection. Interfering signals, random or otherwise, can be rejected if below a certain threshold value. This is accomplished by quantizing the signal, thus introducing quantization noise. *The latter is always larger than the level of interference that can be rejected.* Thus, this valuable property of digital transmission is obtained only by giving up channel capacity. Quantization is a convenience, and not a way to improve channel efficiency. In fact, randomization of the noise, if that is possible, reduces its visibility to a much greater extent than quantization of the signal coarsely enough to reject the noise.

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[7] This is a mixed blessing at long ranges however, as it increases the area of the "no-man's land" between two stations on the same channel 'here neither can be received.

This noise-rejecting ability can be utilized in a long string of amplifiers, or "repeaters," to prevent the accumulation of noise. However, this requires synchronization, resampling, and requantization at each stage. In a system that uses frequency multiplex, such as cable, it also requires demodulation and remodulation of every channel, which is probably impractical.

Multipath and frequency distortion. To the extent that multipath can be modelled as a linear distortion, both of these effects can be eliminated by automatic channel equalization. While the latter is likely to be implemented digitally, the equalization process — its difficulty and effectiveness — is independent of whether an analog or digital modulation method is used. Good equalization is mandatory for the achievement of a high digital data rate. Properly equalized channels would also permit transmission of greatly improved NTSC images to the home.

Nonlinear distortion. This effect is found in cable systems due to cascading large numbers of amplifiers. It is absent in the terrestrial channel itself, although it may be present in the transmitting and receiving circuitry. Such distortion is relatively easy to correct by incorporating a reference signal in the transmission.

Digital Transmission in Analog Channels

There are no purely digital transmission channels, i.e., physical pathways that naturally have a finite number of states. Real channels are usually temporally and amplitude-wise continuous. A digital signal is characterized mathematically as a discrete time series. Such a series is normally converted into an analog signal — a voltage or current — that is defined only at periodic sampling times, and that assumes one of a finite number of amplitude levels at these times. After transmission of such an analog waveform through a physical channel, which inevitably involves some distortion, it is reconverted into a discrete time series by resampling at the appropriate times and requantizing the output to the nearest one of the discrete input levels. The maximum transmission rate in bits/sec is the binary logarithm of the number of possible signal levels times the number of samples per second.[8]

The capacity, C, of an analog channel was shown by Shannon [6] to be

$$C = W \log_2(S/N + 1) \text{ bits/sec},$$

where W is the bandwidth in Hz, and S and N are the mean-square values of signal and noise, respectively. The significance of the channel capacity is that a proof exists that data may be transmitted through such a channel, without error, at rates arbitrarily close to the Shannon capacity. There is no standard procedure for deriving such a coding scheme, however. At the very least, it requires coding long blocks. All current error-correcting codes involve the sacrifice of some channel capacity; it is a rare system that achieves even half the Shannon rate.[9]

[8]What has been described is a baseband system. The same principles apply to signals that may be modulated onto a carrier. The actual information transmission rate (entropy) may be reduced by the statistical structure of the signal, but that need not concern us here. The maximum throughput rate occurs when all levels are equally probable and when successive samples are statistically unrelated.

[9]The efficiency of digital coding is constantly improving. Experimental modems for telephone lines have been built that operate up to 19.2 Kb/s under appropriate channel conditions. No one has ever demonstrated transmission near the Shannon rate for the terrestrial broadcasting channel, howev-

Much is known about coding. One of the important pieces of knowledge is that, in order to have high ficiency (i.e., rates near C), the raw error rate must be fairly high. This means, for the additive white Gaussian noise (AWGN) case,[10] that the signal levels must be spaced somewhat closer than the variance of the noise. Codes can be efficient only for noise levels equal to or larger than the design level. As soon as the noise level gets much below one quantum step, the transmission rate starts falling well below the channel capacity, as is clearly shown in Ungerboek's classical paper on trellis coding. [7]

In the case of analog transmission through the same channel, the full channel capacity is realized at all CNR levels, since, in that case, the maximum possible entropy of the signal is found from the same expression as that used for the channel capacity. This does not necessarily mean that analog transmission is always better than digital transmission. The overall efficiency involves the source coder as well. It is the interaction between the two that must be investigated. As we shall see below, it is not true that digital transmission always means better source coding.

Interoperability. Now that the computer industry has discovered that HDTV may be coming, it has realized that it would be advantageous if HDTV broadcasting standards were readily transcodable to video standards that may be used on multimedia work stations. Square pixels and progressive scan, for example, are preferred. It is also often stated that a digital format is more easily fit into a hierarchy of standards of various spatiotemporal resolutions that may be used in various nonbroadcasting applications. This is not the case.

Because of the use of different TV standards in different parts of the world, a lot of experience in transcoding has been accumulated. It is neither free nor perfect; the more perfect, the more expensive, particularly if the frame rates are different. In any event, the main difficulties are related entirely to the relative resolutions, aspect ratios, and scan rates of the two formats to be mutually converted. The problem is completely unrelated to whether a digital or analog format is involved. In practice, most serious video signal processing is now done digitally. (Some kinds of filtering are still much cheaper in the analog domain.) The conversion between a digital format and its analog version is quite simple as compared with the conversion between two different formats, either analog or digital. In addition, most nonbroadcasting applications will not interface with the terrestrial transmission standard. To the extent that they do, digital versions of the broadcast signal will be found inside every HDTV receiver.

Relationship Between Source Coding and Channel Coding

It is frequently asserted that digital transmission permits better source coding. The implication of this statement is that the data transmitted in the channel bears an arbitrary relationship to the video information, and that therefore any channel error or distortion, as is inherent in analog transmission, would produce unacceptable image degradation. Vector quantization (VQ) is one such form of source coding that requires error-free transmission. With such a system, the function of the channel coder is simply to deliver to the receiver an error-free replica of the output of the source coder. Thus, source coding and channel coding become completely independent. However, none of the current proposals uses VQ or

[10]As a practical matter, all real channels are worse than this. Other kinds of noise, such as impulse noise, phase jitter or phase error in the resampling clock, or imperfect channel equalization that produces intersymbol interference, are all responsible for additional errors. Very accurate clock overy is essential for a low error rate.

any other redundancy-free scheme that demands error-free transmission.

As a logical proposition, joint source/channel coding must at least present the possibility of improved performance, since separate source/channel coding is a special case with an additional constraint. Rather than relying on philosophical principles, however, we can come to some useful conclusions by examining particular systems.

All of the currently proposed all-digital systems are of the same general type. A 2-dimensional discrete cosine transform (DCT) is applied to the motion-compensated frame-to-frame prediction error. Data compression is achieved by discarding low-amplitude coefficients in the transform. The data to be transmitted consists of the chosen coefficients, their identification (i.e., their location in space-frequency), and a small amount of motion information.

The coefficients are essentially picture samples. There is no advantage in digitizing such information unless it is significantly correlated with the identification data, since small errors in picture samples are of no consequence.[11] The quantization noise introduced by digitization is always larger than the channel noise that is suppressed.[12]

Some idea of the advantage that can be taken of the high efficiency achieved by transmitting picture samples in analog form can be gleaned by comparing a prototypical all-digital system of the type described with the MIT-CC system [8], which uses hybrid transmission. In that system, 10 million picture samples are transmitted per second plus 10 Mbits/sec for the digital information. On average, less than one bit plus one analog sample are used to represent each picture sample. In the digital systems, an average of eight bits are used for each coefficient, allowing only about 2 million coefficients per second. To get reasonable picture quality with this small number of coefficients requires very high compression, in this case motion-compensated prediction. The hybrid system, on the other hand, uses no temporal processing at all, getting at least comparable quality using only intraframe processing. If it were to use temporal processing of complexity comparable to that used by the digital systems, the required channel capacity would be reduced by 50% or more. As this example shows, it is not true that digital transmission invariably leads to higher compression in the source coder.

The hybrid system is an example of combined source and channel coding. In this case, the fact that analog samples are transmitted permits the source coder to use an analog representation of the picture samples, which is more efficient than a quantized representation.

An Ideal Terrestrial Broadcasting System

From a performance point of view, an ideal system is simply one that achieves maximum spectrum efficiency, as previously defined. This implies both a high compression ratio and high channel efficiency

[11] It is sometimes stated that digital transmission is required in cases where differential data is being transmitted. This problem can easily be overcome by transmitting the dc component of the signal separately so that the differential data need not be integrated down to zero frequency. This procedure prevents the accumulation of noise in the receiver integration loop.

[12] To the extent that the channel CNR is larger than needed for efficient utilization of channel capacity with a given coding system, the loss due to quantization is even larger. In effect, analog transmission utilizes those output states of the channel that are discarded by quantization, thus achieving higher channel efficiency.

over a wide range of CNR. From a practical point of view, there are many other desirable features, such high reliability under adverse transmission conditions, easy transcodability, and nondisruptive upgradability over time. An ideal system should also lend itself to a feasible transition scenario, which means that equipment costs should be minimized (particularly for the receiver), and it should be possible to make an inexpensive set-top converter to NTSC and other low-resolution formats. This last feature requires some form of progressive transmission together with a method to extract only a part of the transmitted information when the CNR is low and/or the channel equalization is imperfect. The partial equalization and partial extraction should be feasible with low-cost processing circuitry.

High compression. There is a strong relationship between the degree of compression achieved in the source coder and the processing power of the receiver, and therefore its cost. Decisions on this tradeoff are not strictly technical. They depend both on the severity of the spectrum shortage and the speed of penetration of receivers as a function of price. If spectrum were plentiful, we would hardly need any compression at all, and receivers could be very simple. If it were decided that a substantial proportion of the spectrum now allocated to television absolutely had to be given over to mobile services, then more compression would be needed and higher-cost receivers would be inescapable.

It appears, from the studies carried out by the FCC Advisory Committee, that it is reasonable to keep the 6-MHz channel for HDTV, provided that we can use a larger percentage of the allocated channels in each area. The technical question thus becomes the achievement of sufficiently higher quality in this channel, coupled with a low-enough cost, to attract viewers to HDTV. At the same time, the interference performance must be sufficiently better than that of NTSC to enable the FCC to implement its simulcasting decision. If this were achieved, about half the current spectrum could be relinquished when NTSC ultimately goes off the air.

If the proposals that have been made to the FCC represent the state of the art, then the 6-MHz limitation can probably be achieved with some form of subband coding (the DCT is a special case) together with adaptive selection of coefficients or subband samples. The required noise and interference performance can be achieved by adaptive modulation or quantization of the selected samples. Whether temporal processing is required depends on the level of channel efficiency that is attained.

High channel efficiency. The transmission of the same amount of information to all receivers, regardless of CNR, gives very poor channel efficiency and therefore requires temporal processing to meet the bandwidth limitation. However, there are a number of ways, both all-digital and hybrid analog/digital, to get sufficient channel efficiency so that temporal processing is not required.[13] This is bound to reduce the cost of the receiver and would seem to be quite desirable for this reason alone.[14]

Hybrid transmission. Analog transmission achieves the maximum possible transmission efficiency, but does not allow for the error-free transmission that is required for at least part of the data in order to achieve high compression. Thus, a system that uses analog transmission for selected image samples and

[13]There is no well developed theory for efficient transmission in broadcast channels. An early paper by Cover [9] shows that it is possible, but does not provide specific coding methods.

[14]Another reason for preferring intraframe coding, other things being equal, is that it requires no special treatment on scene changes or for material t consists of a sequence of nearly unrelated pictures. It also simplifies editing.

digital transmission for everything else appears to be a good compromise. One way to implement hybrid ansmission is simply to superimpose analog data onto a conventional quadrature amplitude modulation (QAM) system. Figure 4 shows one such scheme in the I-Q (in-phase, quadrature-phase) plane. For example, in the MIT-CC system, the information that is transmitted digitally includes the dc and low-frequency components, synchronization and adaptation information, ancillary data, and audio. The digital data is sent at 10 Mbits/sec using 4-QAM, and the analog data, at 10 Megasamples/sec, is added onto the digital information at a level well below half of the digital steps. The performance of hybrid systems of this type, in terms of channel efficiency, is shown in Figure 5.

There may be ways to achieve both a variation of resolution and SNR with CNR in hybrid systems. If subband coding or its equivalent is used and if the separate frequency components are transmitted at a CNR that falls with frequency, then only those components would be used at any one receiver that actually improve picture quality. In such a scheme, more components would be used at close-in locations, so that the resolution as well as SNR would rise with CNR.

Progressive transmission with different power levels for the separate components. There are also purely digital methods than can take advantage of higher CNR. One such system is being developed at Columbia University. [10] Some form of progressive transmission (in this case pyramid coding) must be used, in which the video information is divided into a number of separate streams. The streams are transmitted at different power levels and the picture quality depends on the number of streams received above the threshold. A simple method is to transmit the separate streams in separate subchannels using 4-QAM, 16-QAM, 64-QAM, and 128-QAM. Either frequency division or time division can be used. The performance two variants of this scheme are shown in Figure 6.

QAM with nonuniform levels. Another quasidigital method having good channel efficiency over a range of SNR is a modification of conventional QAM in which level spacing is nonuniform, as shown in Figure 7. If the I and Q signals are formed in this way, it is clear that each bit has a different bit error rate (BER). If the threshold BER is taken to be the same as that for standard 16-QAM at 16 dB CNR, then there are four thresholds for the modified scheme, spaced about every 6 dB, and the performance is as shown in Figure 8. It is clearly seen that this method, which seems to bear some relationship to trellis coding [9], gives much higher performance than 16-QAM over much of the viewing area.

Variable error protection. One method frequently proposed to achieve higher spectrum efficiency in digital systems is to use a higher degree of error protection for the lower levels of a progressive coding scheme. Unfortunately, since raw BER changes so rapidly with CNR (as much as an order of magnitude for a 1-dB change!) this scheme works only over a very limited range of CNR. What is needed in the terrestrial broadcasting application is a soft threshold of at least 20 to 30 dB; this can only be achieved by having a substantially different raw error rate for the different levels of the data produced by the source coder.

Of course, as a matter of sound engineering, the effects of errors should be minimized to the extent possible. Synchronization should be the last data lost, and the propagation of errors over time should be minimized. Some error-concealment techniques are quite effective, and ought to be used. However, no such techniques, by themselves, can provide the efficient performance over a broad range of CNR as is required in terrestrial broadcasting.

Conclusion

The proposal to use all-digital terrestrial HDTV broadcasting in the US has been carefully examined. Most of the reasons given are found to be erroneous; it is suggested that at least as good service could be provided by digital source coding combined with hybrid channel coding.

Spectrum efficiency is of primary concern to regulatory authorities, such as the FCC, faced with more requests for frequency assignments than there is spectrum available. In order for any HDTV system to have the required high spectrum efficiency, it must deliver an amount of information to each receiver in the viewing area that is a substantial percentage of the theoretical channel capacity at that location. Since CNR, and therefore channel capacity, varies enormously within the viewing area, systems that deliver the same amount of data to everyone, as do all of the currently proposed all-digital systems in the US, have very low transmission efficiency in the central cities. With higher spectrum efficiency, superior service could be delivered to most viewers within a substantially smaller spectrum allocation. Some all-digital systems that achieve higher spectrum efficiency are described. However, hybrid digital/analog transmission permits both very high spectrum efficiency and a degree of data compression at least as high as the currently proposed all-digital systems.

Reliability is an even more important characteristic than image quality in television broadcasting. The fact that digital terrestrial broadcasting at the proposed data rates has not yet been successfully demonstrated is quite troublesome, as it leaves open the possibility that none of the systems proposed in the US will turn out to be satisfactory.

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Figure Captions

Fig. 1 A Generalized Image Processing System

This diagram is meant to permit the characterization of a wide variety of image processing, storage, and transmission systems. The division of coding into two functions is commonly accepted. Source/sink coding takes advantage of the characteristics of images produced by particular sources, such as television cameras, as well as the characteristics of vision of the observers. Channel coding deals with the transmission of data through a physical channel or storage medium.

Fig. 2 A Universal Production and Distribution System

In the future, TV may be distributed to the home by four different kinds of channels in addition to tape or disk recorders. Production of programs is a complicated business involving multiple sources and a good deal of communication. The finished programs must then be distributed to TV stations, cable head-ends, satellite up-links, etc, for international exchange and/or retransmission to viewers. If, as anticipated, different transmission formats are used for each section of the pathway, transcoding is required at many points. (Figs. 1 and 2 are from W.F.Schreiber, *Fundamentals of Electronic Imaging Systems,* Second Edition, Springer-Verlag 1991)

Fig. 3 A Picture with Ghosts, Noise, and Frequency Distortion.

Unfortunately, transmission impairments in analog channels limit image quality in many, if not most, homes. To get good quality reception with any transmission system, analog, digital, or hybrid, these defects must first be removed. In particular, the use of digital transmission does not, by itself, eliminate these impairments; the impairments must be removed in order to permit digital transmission at a useful rate. Once removed, analog picture quality is also greatly improved.

Fig. 4 A Hybrid Transmission Constellation

Analog information can be superimposed on multilevel "digital" signals as long as it is small enough not to cause digital errors. This shows analog data superimposed on a conventional 4-QAM constellation. For a Nyquist rate of 5 MHz, this arrangement would permit the transmission of 10 Megasamples plus 10 Megabits per second.

Fig. 5 Relative Transmission Efficiency of a Hybrid Format

Here we compare the transmission performance of the hybrid format used in the MIT-CC system with conventional 16-QAM and 4-QAM. As can readily be seen, the hybrid format gives about the same performance as QAM in the fringe area, but delivers much more data closer in, where most of the audi-ce exists. The picture quality cannot, of course, be inferred directly from the transmission data rate; the specifics of the transmission systems must also be examined.

Fig. 6 Transmission Efficiency of Multichannel Digital Schemes

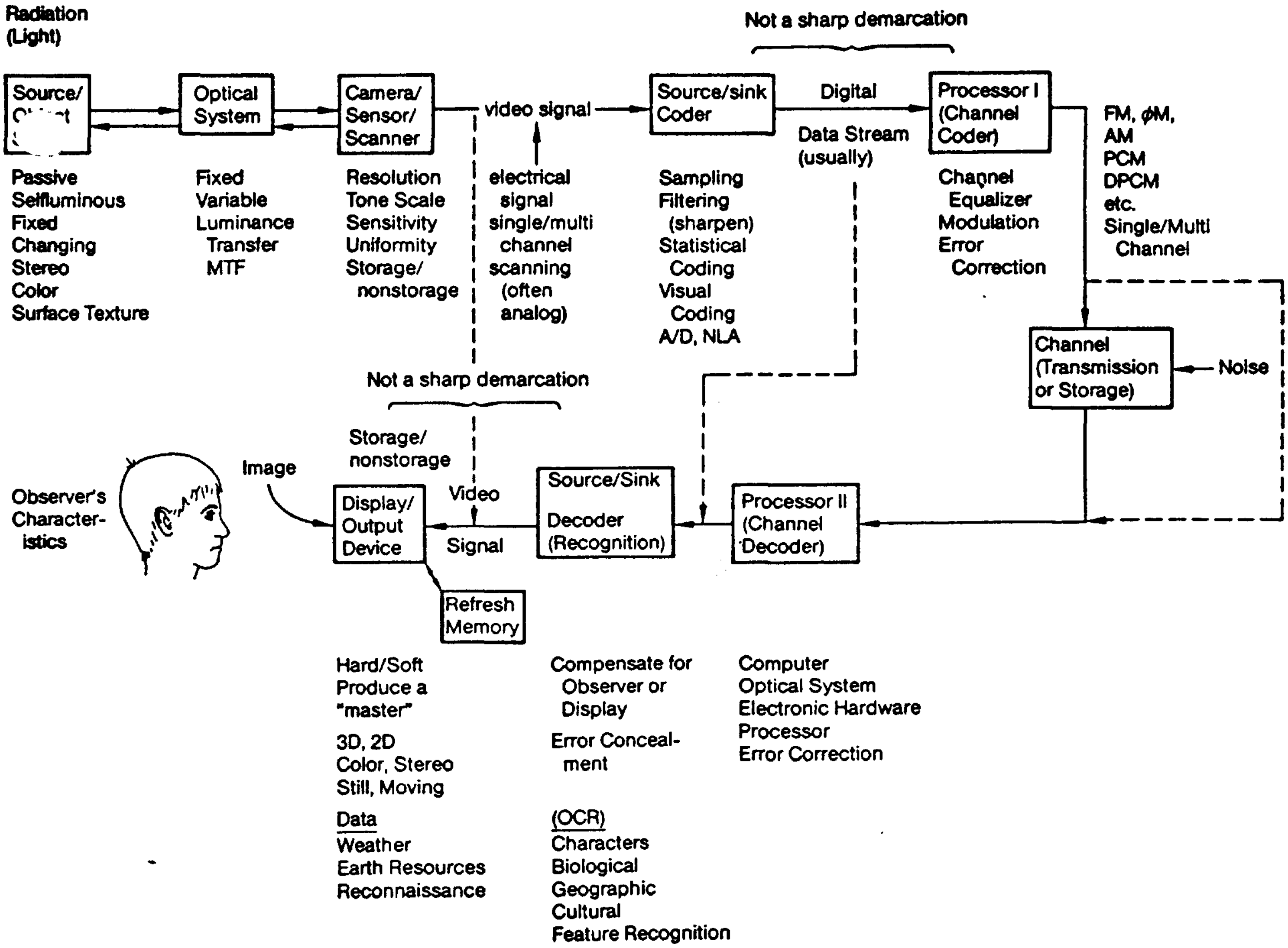
One way to achieve a soft threshold is to divide the channel into subchannels and to transmit with a different format each. Here we use 4-QAM, 16-QAM, 64-QAM, and 256-QAM in four subchannels. The solid line divides the channel into octave bands and the dotted line divides the channel into equal bands. The dashed line shows 16-QAM for comparison. As can easily be seen, the multichannel scheme does better than QAM at high CNR and worse at low CNR.

Fig. 7 256-QAM with Nonuniform Levels

The various level spacings are 1, 2, 4, and 8, corresponding to thresholds of 36, 30, 24, and 18 dB. Errors of the most significant bit are caused by an instantaneous noise level of 4, while errors of the least significant bit by a noise level of .5. Such a scheme is intended to be used with a progressive coding system in which each bit corresponds to a different level of resolution.

Fig. 8 Performance of the Nonuniform-Level QAM Scheme

Here we compare the performance of the scheme of Fig. 7 with 4-QAM through 256-QAM. While the simple QAM schemes are about 6 dB better at their optimum CNR, the nonuniform-level scheme operates quite well over a 24-dB range of CNR. (N.B. The method of calculation used in all these figures is approximate; more refined calculations may yield slightly different results.)



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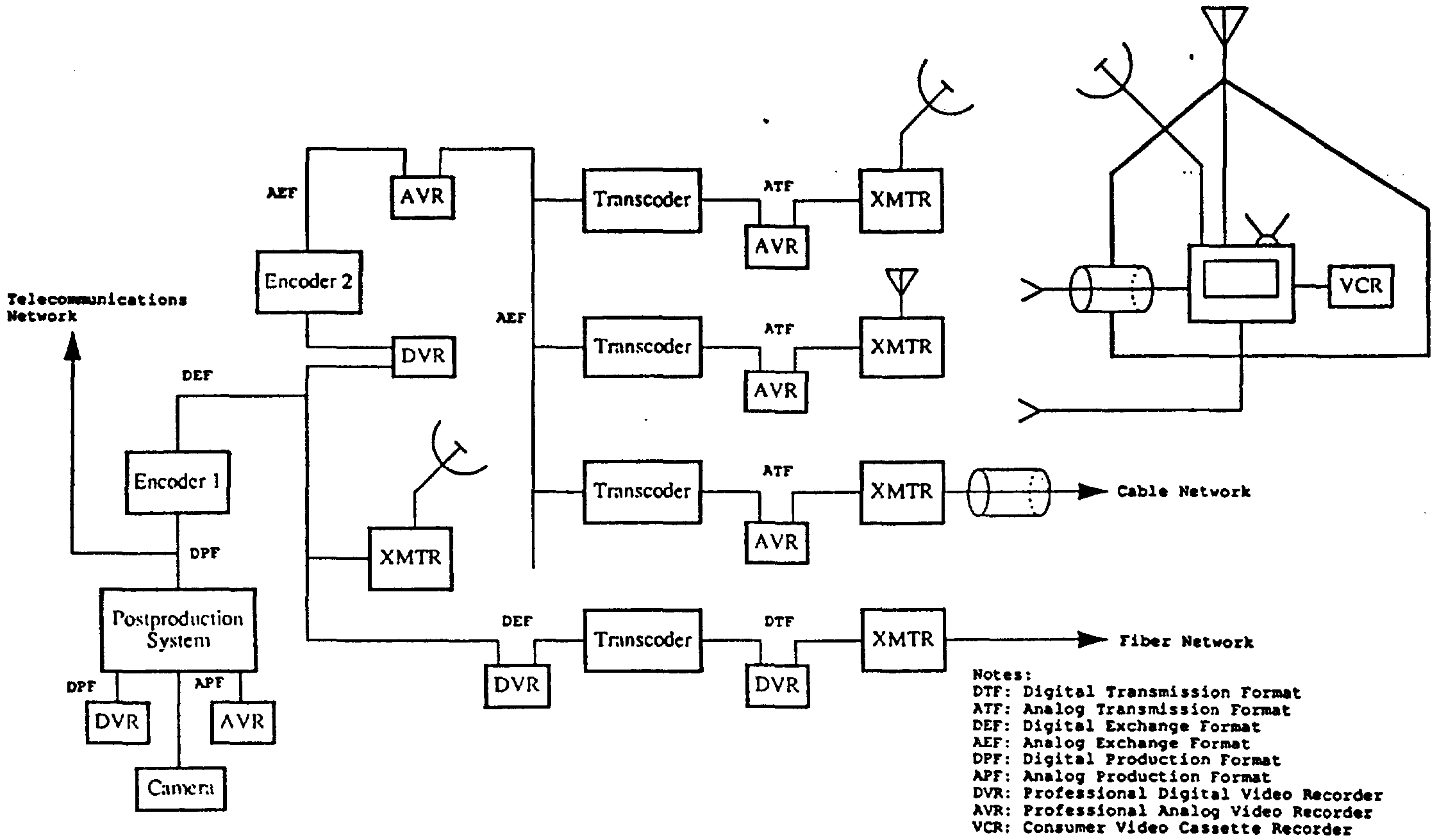

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POOR QUALITY
COPY

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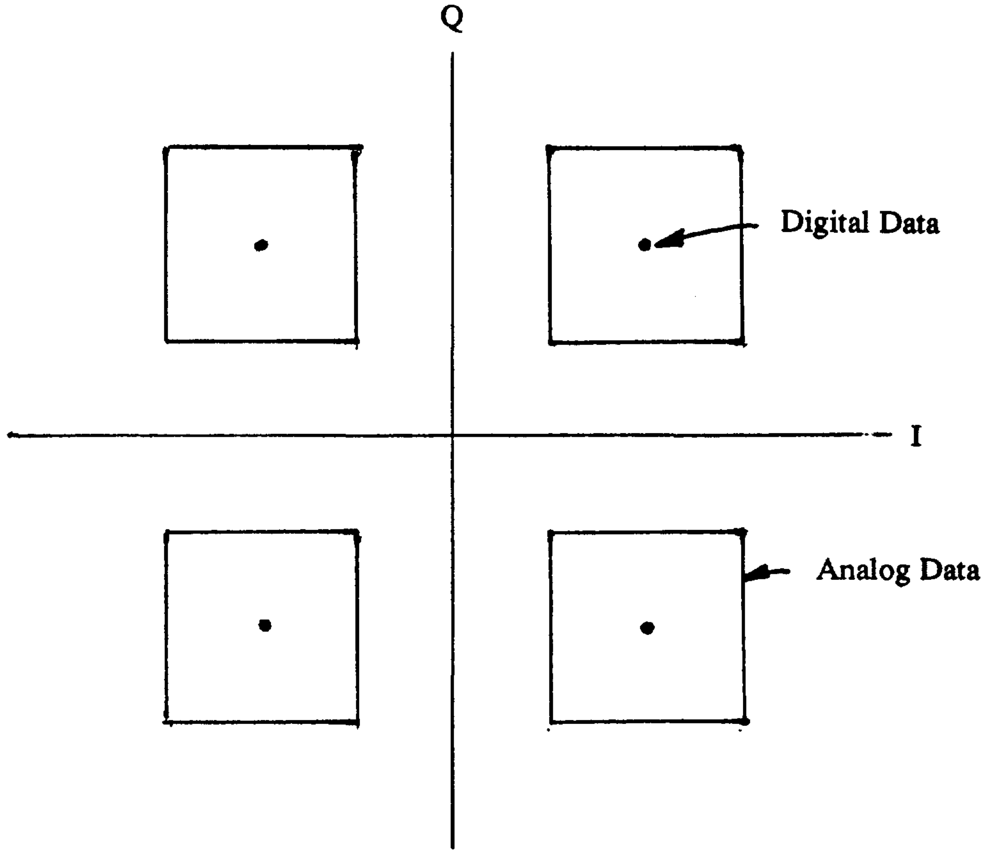

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